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The goal of the project has been to create new tools for control system design and to establish "pathfinders" for implementing new design principles in operational control systems. Four topics were addressed in the subject project:

- Neural Networks for System Modeling and Nonlinear Control
- Stochastic Robustness of Control Systems
- Computer-Aided Control System Design
- Optimal Rule-Based Guidance for Autonomous Vehicles

The principal result of the first task is the development of a new method for training neural networks using extended Kalman filtering to match not only multivariate functions but the gradients of their surfaces. The principal result of the second task is the development of a powerful new method for characterizing the robustness of control systems and for designing controllers with satisfactory stability and performance robustness. The principal result of the third task is the identification of a new computational structure for multidisciplinary control system design. The principal result of the fourth task is a new approach for designing real-time rule-based controllers that can operate in uncertain environments, with particular application to the guidance of vehicles on a roadway with traffic.

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Robert F. Stengel
Professor
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ABSTRACT

The overall goal of the project has been to create new tools for control system design and to establish "pathfinders" for implementing new design principles in operational control systems. Four topics were addressed in the subject project:

- Neural Networks for System Modeling and Nonlinear Control
- Stochastic Robustness of Control Systems
- Computer-Aided Control System Design
- Optimal Rule-Based Guidance for Autonomous Vehicles

The first three tasks were initiated at the start of the project. The fourth task was added with the support of the U.S. Army Tank and Automotive Command. In addition, several papers related to the general area of intelligent control were partially supported by this contract. The project has produced 23 technical papers and one Ph. D. thesis to date. Additional theses will be completed in the coming months.

The principal result of the first task is the development of a new method for training neural networks using extended Kalman filtering to match not only multivariate functions but the gradients of their surfaces. This task also sheds light on the accuracy with which functions can be approximated by neural networks. The principal result of the second task is the development of a powerful new method for characterizing the robustness of control systems and for designing controllers with satisfactory stability and performance robustness. This research revealed wide disparity in the robustness of controllers designed using other methods, and it called into question the use of both classical and modern stability margins (i.e., gain/phase margins and singular-value margins) to characterize robustness. The principal result of the third task is the identification of a new computational structure for multidisciplinary control system design. The structure is based on a graphics user interface that facilitates model building, control design, and system evaluation, and it is based upon object-oriented programming. The principal result of the fourth task is a new approach for designing real-time rule-based controllers that can operate in uncertain environments, with particular application to the guidance of vehicles on a roadway with traffic.

The period of performance for this contract was July 1, 1989 to June 30, 1992.

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1. STATEMENT OF THE PROBLEM

1.1 Neural Networks for System Modeling and Nonlinear Control

The principal objective is to develop computational neural networks that identify and characterize dynamic system structures and parameters. A particular goal is to approximate multivariate functions smoothly and precisely. Neural network training may occur off-line, as in post-processing of test data, or on-line, as in adaptive nonlinear control. In the present application, the trained networks represent force and moment coefficients of an aircraft as nonlinear functions of the state and control.

1.2 Stochastic Robustness of Control Systems

The principal objective is to develop methods for robust-control-system *analysis* and *synthesis* based on Monte Carlo evaluation. The goals of this research are to develop improved methods for assessing uncertainty effects on the stability and performance of actively controlled systems and to establish a comprehensive basis for designing reliable computational control systems. Monte Carlo evaluations of the stability and performance metrics determine the likelihood that control design goals will be achieved. A comprehensive parameter search is used to define a controller that maximizes closed-loop stochastic robustness. Unlike frequency-domain methods, this method treats multivariate objectives directly rather than inferring robustness from indirect, scalar measures.

1.3 Multidisciplinary Computer-Aided Control System Design

The principal objective is to incorporate "machine intelligence" in computer-aided control system design (CACSD). Initial development focuses on *FlightCAD*, a domain-specific program for flight-control design that contains several modeling, synthesis, simulation, and evaluation alternatives. It is built around a desktop metaphor that features pull-down menus and dialog boxes containing design alternatives and documents with multiple layers of information.

1.4 Optimal Rule-Based Guidance for Autonomous Vehicles

The principle objective is to develop improved methods for real-time command and control using artificial intelligence and stochastic control theory. This requires the definition of global goals and decision-making processes. The methodology combines an expert system with stochastic optimal control; heuristic knowledge specifies guidance objectives and reduces the search space for optimization, as well as improving the robustness of solution. Optimal estimation minimizes the effects of uncertainty in situation assessment and goal definition. A particular objective is to simulate autonomous optimal control of an automobile on a highway.

2. SUMMARY OF IMPORTANT RESULTS

2.1 Neural Networks for System Modeling and Nonlinear Control

The principal publications related to this task are [1] to [4]. We have developed an approach that allows learning to be conducted on-line, as needed for adaptive control, or off-line, as required for post-processing of empirical data. An extended Kalman filter (EKF) estimates histories of both the state vector and a vector of forces and moments. Together with control settings, the state estimate forms the input (feature) vector of the neural network, while the vector of forces and moments is the desired output required for training. Matching a function's partial derivatives as well as its value produces a marked reduction in fit error by comparison to earlier methods. A separate EKF estimates the network weights; its training ability is impressive, yielding force coefficient histories that are virtually identical to the true values. Correlation among input variables in the training set tends to mask true functional relationships in the network. Recent training results show that a randomized input produces excellent learning, while simulated flight inputs are constrained by the correlation in flight motions.

2.2 Stochastic Robustness of Control Systems

The principal publications related to this task are [5] to [17]. Stochastic robustness analysis offers a rigorous yet straightforward alternative to other robustness metrics that is simple to compute and is unfettered by normally difficult problem statements, such as non-Gaussian statistics, products of parameter variations, and structured uncertainty. The analysis embraces both stability and performance metrics, handling qualities requirements, and more general responses. Binomial confidence intervals provide statistical bounds on the probability of instability and on performance metrics. Statistical comparisons of control system robustness also are rendered through confidence intervals. Both stability and performance metrics resulting from stochastic robustness analysis provide details relating system specifications intrinsic to a given application and control system design parameters.

A general sequence for synthesis based on implicit-model-following control is as follows: choose a suitable model, choose a linear-quadratic-regulator (LQR) structure, design the LQR to minimize a stochastic-robustness metric, choose an estimator structure, design a linear-quadratic-Gaussian regulator (LQGR) to minimize a stochastic-robustness metric, accept the result or iterate. The 1991 American Control Conference Benchmark Problem was chosen as an initial test case. This problem is similar to the 1990 version of the problem; hence, it is possible to compare our design with ten controllers designed for the earlier challenge. Our controllers compare favorably with the designs produced by other researchers. Furthermore, the stochastic synthesis technique provides direct control over important design criteria, such as stability, settling time, and control usage. Stochastic robustness analysis and synthesis has a significant role to play in computer-aided control system design.

2.3 Multidisciplinary Computer-Aided Control System Design

The principal publication related to this task is [18]. The computer program *FlightCAD* has a modular structure that will be expanded over an extended period of time. *FlightCAD* is intended to address needs within the flight-control domain. It has broad capabilities for modeling aircraft systems and subsystems, for integrating their coupled effects in simulation, and for designing flight control systems over the entire flight envelope. The program uses a desktop metaphor to organize the design process, with a menu bar, pull-down lists of design functions and alternatives, dialog boxes, and multiple display windows. *FlightCAD* is implemented using features of the NeXT Computer for designing screens, integrating code produced in several programming languages, and multitasking within a UNIX environment.

The top-level menu items describe *FlightCAD's* functions and features. Several of the items are common to most window-based applications (such as *Info* and *Edit*); those that are specific to *FlightCAD* include *Block Diagram, Model, Design, Analyze*, and *Activate*. Selecting a menu item brings up the next level of the menu hierarchy. This "point-and-click" process defines the equations of motion to be used for control design and simulation. Most remaining choices can be selected in the same way, and the NeXT-Step environment makes adding menu items an easy process. *FlightCAD*'s focal point is the block diagram. The *FlightCAD* document contains diagrams drawn by the user to represent the system. Each block has several labels that describe its properties. A block can contain a function, or another block diagram. Double-clicking on the block either brings up a text editing window with the function or a *CADdoc* containing the block diagram, as appropriate. In this way, the user can navigate through the existing hierarchy of inner and outer loops.

Block diagram templates facilitate system development. This format allows quick development in as much detail as desired. If a given block is not required, its function is set to unity; hence, a control designer could simulate just the plant dynamics at first, then check the effect of pressure or temperature variations, add actuator and sensor dynamics, and finish with a controller that takes all of this into account. *FlightCAD* compiles the functions represented by block diagrams into GNU C source code. At each step, *FlightCAD* compiles only those portions of the code that have changed since the last compilation, allowing development to occur in stages. This feature supports rapid prototyping and comparison of competing designs.

FlightCAD contains advanced iteration and search capabilities that enhance modeling, design, and analysis. In any phase, the controller can be evaluated at selected, tabulated, or random points of the operating range space, supporting point designs, designs along (or in the vicinity of) nominal path histories, or designs that span the entire flight envelope. This feature is useful not only during design but in the evaluation phase, when the likelihood of satisfactory stability and performance must be determined. Control and estimation design algorithms ultimately will include a wide range of alternatives, from classical methods for single-input/single-output systems to modern methods of multi-input/multi-output design; from linear, time-invariant models to nonlinear, time-varying models; and for continuous and sampled-data controllers.

2.4 Optimal Rule-Based Guidance for Autonomous Vehicles

The principal publications related to this task are [19] to [22]. (Reference 22 was produced under earlier contract.) This research addresses the feasibility of a real-time, rule-based guidance system for an autonomous vehicle on a roadway. The inputs to the system are parameters describing the traffic situation, road geometry, vehicle state, and an operator-selected goal. The output of the system consists of guidance parameters that command control logic governing the throttle, steering angle, and brakes. In early research, a dynamic expert system accomplished this guidance task under the assumption that all inputs were available deterministically, i.e., without error. Later research investigates the types and effects of uncertainties encountered in a more realistic environment, and it proposes a stochastic methodology to extend the expert system to handle information that is known only in a probabilistic way.

2.5 Intelligent Control

The principal publications are [23] to [26]. In the course of conducting the project, insights on the general topics of failure-tolerant and intelligent control were collected. An overview of failure-tolerant control was presented, beginning with robust control, progressing through parallel and analytical redundancy, and ending with rule-based systems and artificial neural networks. By design or implementation, failure-tolerant control systems are "intelligent" systems. All failure-tolerant systems require some degree of robustness to protect against catastrophic failure; failure tolerance often can be improved by adaptivity in decision-making and control, as well as by redundancy in measurement and actuation. Reliability, maintainability, and survivability can be enhanced by failure tolerance, although each objective poses different goals for control system design. Artificial intelligence is helpful for integrating and codifying failure-tolerant control systems, not as an alternative but as an adjunct to conventional design methods.

The capabilities of control systems can be enhanced by designing them to emulate functions of natural intelligence. Intelligent control functions fall in three categories. *Declarative* actions involve decision-making, providing models for system monitoring, goal planning, and system/scenario identification. *Procedural* actions concern skilled behavior and have parallels in guidance, navigation, and adaptation. *Reflexive* actions are spontaneous, inner-loop responses for control and estimation. Intelligent control systems learn knowledge of the plant and its mission and adapt to changes in the environment. Cognitive models form an efficient basis for integrating "outer-loop/inner-loop" control functions and for developing robust parallel-processing algorithms.

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17. Stengel, R. F., "Probabilistic Evaluation of Control System Robustness," presented at the *IMA Workshop on Control Theory and Its Applications*, Minneapolis, Oct 1992 (to appear in research monograph).

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4. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

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Laura Ryan Ray	Ph. D. student. Degree completed: June 1991.
Dennis J. Linse	Ph. D. student. Expected date of completion: Dec. 1992.
Axel Niehaus	Ph. D. student. Expected date of completion: Dec. 1992.
Subrata Sircar	M. S. E. student. Expected date of completion: Dec. 1992.
Christopher I. Marrison	Ph. D. student. Expected date of completion: Aug. 1993.
Sandeep S. Mulgund	Ph. D. student. Expected date of completion: Aug. 1993.